photonics

MDPI

Article

Short-Term Peripheral Contrast Reduction Affects Central Chromatic and Achromatic Contrast Sensitivity

Antonia Neumann [1,*], Alexander Leube [2], Najma Nabawi [1], Yannick Sauer [1], Peter Essig [1], Katharina Breher [1,2] and Siegfried Wahl [1,2]

[1] Institute for Ophthalmic Research, University of Tübingen, 72076 Tübingen, Germany; najmanabavinn@gmail.com (N.N.); yannick.sauer@uni-tuebingen.de (Y.S.); peter.essig@uni-tuebingen.de (P.E.); katharina.breher@zeiss.com (K.B.); siegfried.wahl@zeiss.com (S.W.)

[2] Carl Zeiss Vision International GmbH, 73430 Aalen, Germany; alexander.leube@zeiss.com

* Correspondence: antonia.neumann@uni-tuebingen.de

Abstract: Peripheral retinal contrast reduction is suggested as a potential myopia control strategy. However, the underlying mechanism is yet unknown. Therefore, this study investigated the influence of peripheral contrast reduction on central chromatic and achromatic contrast sensitivity (CS). A total of 19 participants were included. Peripheral contrast reduction was induced via Bangerter foils of 0.4 and 0.8 density, each with a clear central zone of 8.0 mm diameter. Central achromatic and chromatic (for S-, M-, and L-cone types) CS was measured at 3 and 12 cpd in a 2-IFC psychophysical procedure. CS was tested monocularly at 0, 30, and 90 min of adaptation time, while the fellow eye was covered by an infrared filter. With the filter in place, pupil size was controlled to be smaller than the clear central aperture. Data were analyzed using linear mixed models. Cone-type CS showed significant differences among each other (all $p < 0.05$), except for the achromatic and L-cone type ($p = 0.87$). The minimum sensitivity was found with the S-cone type and the maximum with the M-cone type. Central achromatic and chromatic CS were equally affected by diffusion. The level of peripheral diffusion also influenced CS, while the 0.8 Bangerter foil led to a higher reduction in CS compared to the 0.4 Bangerter foil ($p = 0.0008$) and the control condition ($p = 0.05$). A significant reduction in CS occurred between 30 and 90 min of adaptation time ($p < 0.0001$). The current study found that peripheral contrast reduction impacted central achromatic and chromatic CS equally. It further showed that the amplitude of reduction was influenced by the level of diffusion, with the reduction becoming more pronounced over time.

Keywords: contrast adaptation; scattering; diffusion; contrast reduction; peripheral contrast reduction; contrast sensitivity; visual adaptation; refractive development; myopia

Citation: Neumann, A.; Leube, A.; Nabawi, N.; Sauer, Y.; Essig, P.; Breher, K.; Wahl, S. Short-Term Peripheral Contrast Reduction Affects Central Chromatic and Achromatic Contrast Sensitivity. *Photonics* **2022**, *9*, 123. https://doi.org/10.3390/photonics9030123

Received: 1 February 2022
Accepted: 19 February 2022
Published: 22 February 2022

1. Introduction

Physiological ocular refraction changes during early life are known as refractive development. While hyperopia is common in newborns, it reduces during childhood, also called emmetropization. If the emmetropization process is disturbed, hyperopia may persist or myopia and/or astigmatism may occur [1,2]. Moreover, emmetropization processes depend on multiple factors including the balance of central and peripheral visual experiences [3–5]. Here, the peripheral retina might be of importance in the ability to derive blurred and diffused contrast signals [5], as well as in contrast adaptation processes [6–13].

Retinal contrast reduction is associated with retinal image degradation, based on various optical factors, such as defocus, astigmatism, higher order aberration, or scattering [12,14]. The role of peripheral contrast reduction and the related contrast adaptation processes in refractive development have not yet been fully clarified.

Contrast adaptation is a form of cortical neuroplasticity, where the visual response is re-calibrated to compensate for variations in sensitivities [12]. Previously, improved visual performance was shown to occur in response to blurred and diffused stimuli [11,12,15].

Along this line, a novel spectacle lens design for myopia control was developed to reduce peripheral contrast via diffusion while maintaining clear central vision by a clear aperture [16,17]. In the related non-peer-reviewed article, reduced axial elongation was reported and a protective effect regarding myopia progression was proposed, based on the strategy of reduction in abnormal high contrast signaling in the retinal periphery [16,17].

The impact of contrast reduction in the retina including the separate stimulation of photoreceptors is still unknown, while the sensitivity of cones themselves has already been established. Short-wavelength light sensitive cones (S-cones) exhibit a decreased sensitivity compared to middle-wavelength light sensitive cones (M-cones) and long-wavelength light sensitive cones (L-cones) [18,19].

Achromatic and chromatic contrast adaptation to diffusion was measured centrally after central adaptation [6,7,12,20–24] or peripherally after peripheral adaptation so far [6,7,22,25], however, not centrally after peripheral adaptation. Therefore, this study aimed to investigate the short-term influence of different levels of peripheral contrast reduction in central cone-specific CS, in order to evaluate a potential mechanism that explains the novel myopia control strategy.

2. Materials and Methods

2.1. Inclusion and Exclusion Criteria

This prospective study was carried out at the Institute for Ophthalmic Research at the University of Tübingen. The study protocol followed the Declaration of Helsinki and data protection regulations. Approval was obtained by the ethics committee of the Faculty of Medicine of the University of Tübingen. Before the measurements, participants signed a written informed consent form after the content and possible consequences of the study had been explained. Inclusion criteria were self-reported ocular health, visual acuity of $\leq$0.1 logMAR, and normal color vision. Participants were excluded with present self-reported systemic and ocular abnormalities, anisometropia of $>$1 D, a history of orthokeratology wear or corneal refractive surgery, and age $<$18 and $>$40 years.

2.2. Apparatus

The objective refraction was measured with wavefront aberrometry (i.Profiler plus, Carl Zeiss Vision GmbH, Aalen, Germany) and was confirmed with subjective refraction using ZEISS VISUSCREEN 500 and ZEISS VISUPHOR 500 (Carl Zeiss Vision GmbH, Aalen, Germany). For the psychophysical experiment, the individual's sphero-cylindrical correction using trial lenses (Oculus BK 1/T, Oculus GmbH, Wetzlar, Germany) was mounted into a trial frame (Oculus B5, Oculus GmbH, Wetzlar, Germany) with a vertex distance of 12 mm in front of the right eye. The participants right eyes were fully corrected according to the subjective refraction. Bangerter foils (Breitfeld & Schliekert GmbH, Karben, Germany) with a density of 0.4 and 0.8, each with a 8.0 mm clear central aperture were additionally applied to the right eye to induce the desired peripheral contrast reduction. The 0.4 Bangerter foil reduces the visual acuity by five lines (e.g., from 1.0 to 0.4 decimal visual acuity) and the 0.8 Bangerter foil by one line (e.g., from 1.0 to 0.8 decimal visual acuity). For clarification reasons, the naming remains at 0.4 and 0.8 Bangerter foil in the following sections. Each of the Bangerter foils were pasted and centered on a plano lens and then mounted into the backside of the trial frame, see Figure 1. Subsequently, the clear central aperture was centered in front of the individual's pupil. The slots at the front of the frame were reserved for the sphero-cylindrical correction. The participants pupillary response was assessed on the left eye with infrared photorefraction, using the PowerRefractor [26]. Therefore, an additional infrared filter was mounted into the trial frame in front of the participants left eyes, see Figure 1. Head position was stabilized with a chin and forehead rest. To verify normal color vision respective the inclusion criteria, the Ishihara test (Kanehara Trading Inc., Tokyo, Japan) was conducted prior to the actual experiment.

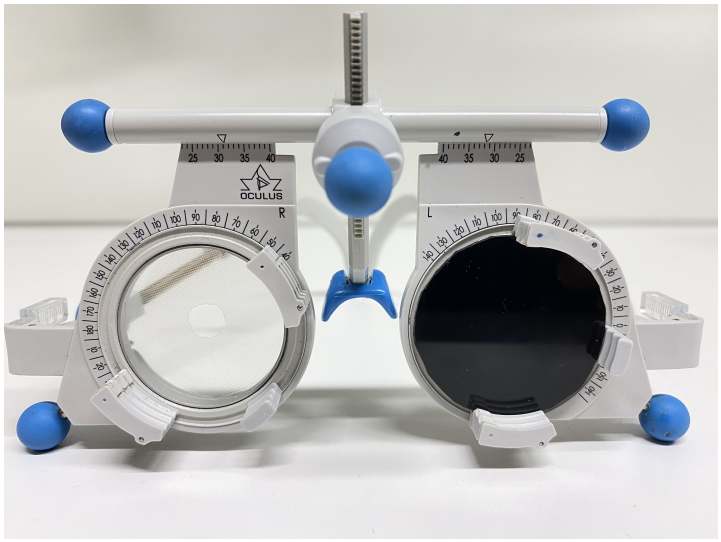

Figure 1. Trial frame example with the 0.4 Bangerter foil pasted on a plane lens, while the clear central aperture is centered to the lens, inserted at the back side of the trial frame—in front of the right eye. The slots on the front side were reserved for the individual sphero-cylindrical correction and the near compensation lens. The infrared filter on the left eye was used to measure the pupil size.

All psychophysical test procedures were programmed in MATLAB (MATLAB R2020a, MathWorks Inc., Natick, USA) using the Psychtoolbox [27,28], Palamedes toolbox [29], and DataPIXX toolbox (VPixx Technologies Inc., Saint-Bruno, QC, Canada) extensions. An LCD display (VIEWPixx, VPixx Technologies Inc., Saint-Bruno, QC, Canada) with a mean luminance of 40 cd/m², a resolution of 1920 × 1200 pixels, and a 12 bit graylevel resolution was used for stimuli presentation in a distance of 75 cm. The luminance nonlinearity of the screen was corrected by using a color lookup table computed for gamma correction.

2.3. Stimuli

The cone-type-specific stimuli were created using the silent substitution method [18,30]. This method elicits changes in a specific cone type only, after modulation of the red, green, and blue screen channels, to present the desired cone-type-specific color direction. The respective Gabor patch was produced using the CIE x- and y-coordinates of the peak modulations of the cone type stimuli, as described elsewhere in more detail [18,31,32]. The Gabor patch was produced with a size of 1.7° of visual angle, spatial frequencies of 3 and 12 cpd, and a 2-D Gaussian envelope of $\sigma = 0.1°$. The color properties of the sinusoidal pattern of the Gabor patch were modified to represent an achromatic, as well as the three cone-specific stimuli for S-, M-, and L-cones, see Figure 2. The test stimulus was presented randomly in four different orientations (0°, 45°, 90°, 135°) against a constant gray background field. Moreover, the size and spatial frequencies of the stimuli were corrected for image magnification artifacts resulting from the participants lens corrections.

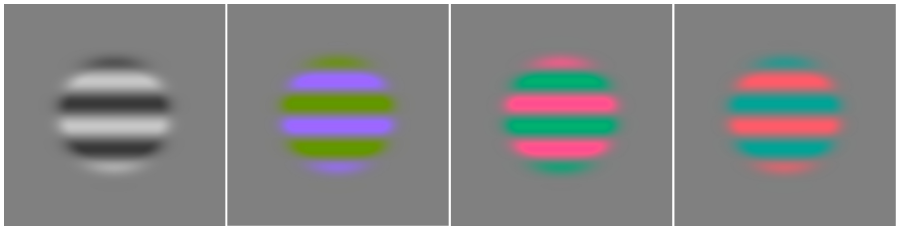

Figure 2. High-contrast versions of the achromatic, S-, M-, and L-cone type Gabor patches with a spatial frequency of 3 cpd.

2.4. Study Protocol

The Tuebingen CS Test [33] was taken as a basis and subsequently modified to a two-interval forced-choice (2IFC) psychophysical test method. An adaptive staircase procedure was used to automatically select the contrast level on each trial as the search for the contrast threshold was performed. Here, the CS values have been obtained as the reciprocal of the contrast threshold. One experimental session contained 8 different blocks, each consisted of 30 trials while the order of the cone-type-specific stimuli (achromatic, S-, M-, and L-cone) and spatial frequencies (3 and 12 cpd) were presented randomized. One trial consists of two 153 ms intervals separated by a 400 ms inter-stimulus break with a sound, whereas one interval contained the stimulus, and the other interval was blank (gray screen), as depicted in Figure 3. The orientation of the Gabor patches was randomized for each trial. According to the 2IFC psychophysical procedure, the participants had to respond with a key press at which interval the target was presented. During the response time, a gray circle around the stimulus location with the double diameter of the grating served as a fixation point on the gray background. The same test procedure was performed at the initial T_0 session, after 30 min (T_{30}) and 90 min (T_{90}) for each of the three conditions—control (clear vision, without diffusion) and 0.4 and 0.8 Bangerter foil. The conditions were randomized and took place on three different days, however, at the same time of the day to eliminate diurnal variations of vision and attention. An additional +1.25 D lens was implemented in front of the right eye as accommodation compensation to the screen distance during measurements, which took around 8 to 9 min. For all participants, CS testing was conducted monocularly by the right eye and pupil size investigation by the left eye, based on the arrangement possibilities of the test setup. Between the sessions, the participants were advised to watch a standard movie from a distance of 2 m, to avoid accommodation.

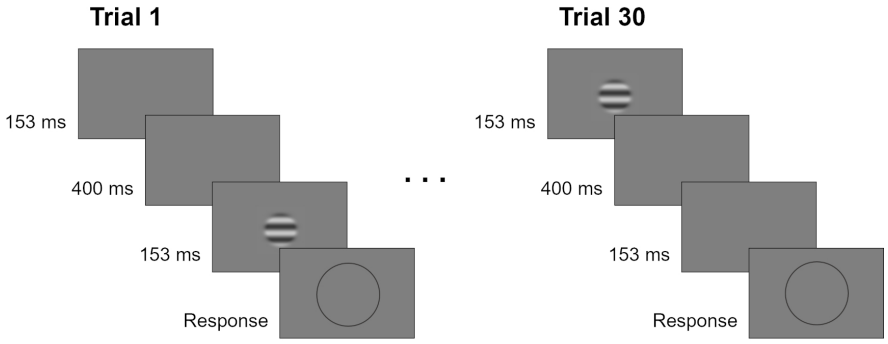

Figure 3. Two-interval forced-choice sequence for one achromatic test block. This sequence was repeated for eight randomized blocks in total: the achromatic block and three chromatic blocks for spatial frequencies of 3 and 12 cpd.

2.5. Statistical Data Analysis

Statistical analysis was conducted using linear mixed models with the statistics software RStudio (RStudio Version 1.4.1717, R Core Team 2021) to identify influencing factors separately on CS measured in log(CS). Before statistical analysis, the data underwent outlier detection. Thereby, data points that were more than three interquartile ranges (IQR) outside of the median were removed. Within the model, CS figured as dependent variable, with participants as random factor and four within-subject factors: spatial frequency (3 and 12 cpd), stimuli type (S-, M-, L-cone, achromatic), adaptation time (T_0, T_{30}, and T_{90}), diffusion level (control, 0.4 BF, and 0.8 Bangerter foil, each with a clear aperture of 8.0 mm). For every possible factor combination with and without interactions, a linear mixed model was designed. All final models were compared by the value of the Akaike information criterion (AIC) to find the most suitable model (AIC comparison, see Table S1). The model with the lowest AIC was selected for further analysis for each parameter CS. Significant effects underwent subsequent post hoc testing using estimated marginal means (least-squares

mean and standard error). The significance level was set to $\alpha = 0.05$ and significant effects were defined by $p < 0.05$.

3. Results

3.1. Participant Data

A total of $n = 19$ adults were included in the study (16 females and 3 males). The mean age was age 24.21 ± 3.68 years (ranging from 19 to 31 years). The right eye's subjective refraction resulted in a spherical equivalent of −1.61 D ± 2.16 D with a minimum of −6.25 D and a maximum of 0.75 D. Eye biometry examination revealed an axial length of 24.28 ± 1.18 mm and a pupil size of 4.73 ± 0.68 mm.

3.2. Contrast Sensitivity

The averaged log(CS) values for the different time points T_0 to T_{90} separated for the diffusion condition are presented in Table 1 and Figure 4. CS was influenced significantly by all model factors. However, no significant interactions between these factors were found ($p = 0.86$).

Table 1. Log(CS) (median ± IQR) for the different measurement conditions ($n = 19$ participants).

		Control			0.4 Bangerter Foil			0.8 Bangerter Foil		
		T_0	T_{30}	T_{90}	T_0	T_{30}	T_{90}	T_0	T_{30}	T_{90}
3 cpd	Achromatic	1.60 ± 0.13	1.55 ± 0.23	1.58 ± 0.07	1.58 ± 0.28	1.59 ± 0.19	1.58 ± 0.11	1.62 ± 0.07	1.58 ± 0.11	1.60 ± 0.24
	S-cone	0.95 ± 0.11	0.95 ± 0.15	0.90 ± 0.19	0.92 ± 0.32	1.01 ± 0.32	0.96 ± 0.09	0.98 ± 0.37	0.92 ± 0.25	0.87 ± 0.28
	M-cone	1.64 ± 0.30	1.67 ± 0.22	1.64 ± 0.27	1.78 ± 0.12	1.68 ± 0.30	1.66 ± 0.13	1.54 ± 0.51	1.67 ± 0.24	1.55 ± 0.36
	L-cone	1.62 ± 0.19	1.62 ± 0.48	1.61 ± 0.15	1.68 ± 0.12	1.63 ± 0.16	1.49 ± 0.22	1.66 ± 0.24	1.59 ± 0.20	1.50 ± 0.31
12 cpd	Achromatic	1.06 ± 0.47	1.20 ± 0.22	0.94 ± 0.56	1.34 ± 0.40	1.14 ± 0.38	1.16 ± 0.71	0.84 ± 0.80	1.30 ± 0.53	0.94 ± 0.74
	S-cone	0.47 ± 0.36	0.51 ± 0.30	0.45 ± 0.45	0.51 ± 0.34	0.57 ± 0.35	0.43 ± 0.59	0.41 ± 0.45	0.44 ± 0.31	0.32 ± 0.46
	M-cone	1.30 ± 0.30	1.32 ± 0.36	1.15 ± 0.61	1.31 ± 0.49	1.33 ± 0.46	1.16 ± 0.88	1.22 ± 1.14	1.09 ± 0.91	0.94 ± 0.77
	L-cone	1.13 ± 0.22	1.04 ± 0.71	1.00 ± 0.96	1.26 ± 0.31	1.26 ± 0.76	0.96 ± 1.15	1.26 ± 0.67	1.21 ± 0.29	1.01 ± 0.67

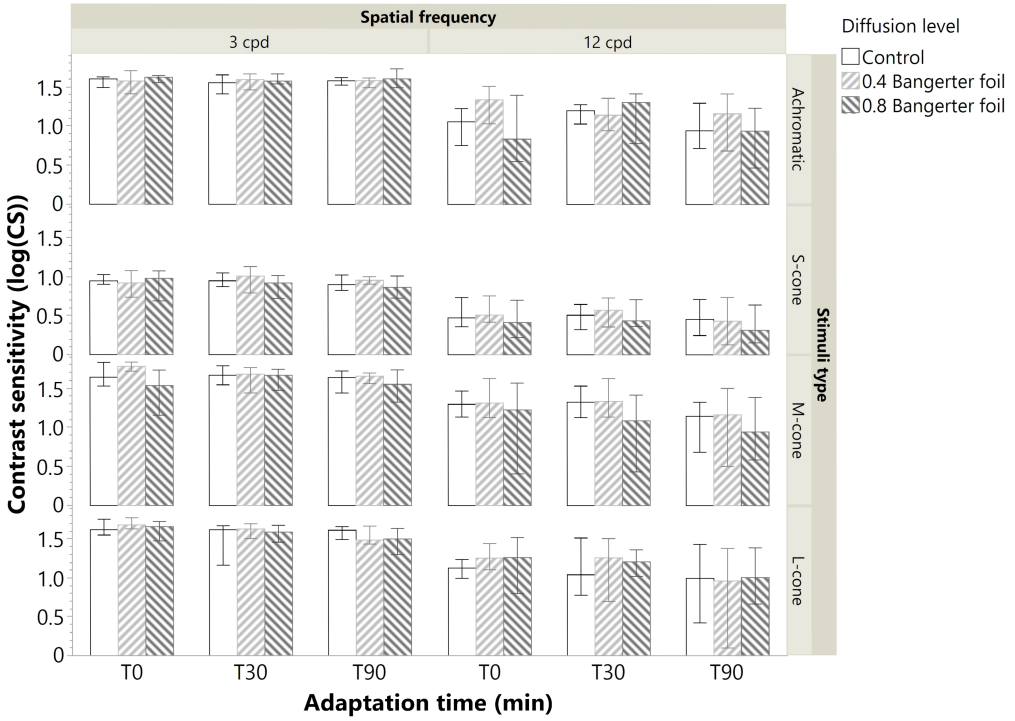

Figure 4. Median ± IQR in log(CS) for the different diffusion levels, spatial frequencies, stimuli types, and adaptation times ($n = 19$ participants).

3.2.1. Spatial Frequency

As expected, CS was significantly higher at 3 cpd (1.33 ± 0.06 log(CS)) than at 12 cpd (0.91 ± 0.06 log(CS)) over all conditions ($p < 0.0001$). Moreover, CS at 12 cpd revealed slightly higher inter-subject variations than at 3 cpd. Interactions with the other factors were not found; consequently, no effects of cone types, the level of diffusion, or adaptation time were exhibited.

3.2.2. Cone Type Specific Contrast Sensitivity

The S-cone type exhibited the lowest CS of 0.67 ± 0.06 log(CS) for both spatial frequencies, whereas the M-cone revealed the highest CS values of 1.32 ± 0.06 log(CS). L-cone type (1.26 ± 0.06 log(CS)) and achromatic type (1.24 ± 0.06 log(CS)) were found closer to the maximum than the minimum. However, significant effects were found for CS in all cone types ($p < 0.05$), except for the comparison of the achromatic and L-cone type (-0.02 ± 0.02 log(CS); $p = 0.87$). Furthermore, L- and M-cone type differed less significantly (-0.06 ± 0.02 log(CS); $p = 0.01$) than achromatic and M-cone type (-0.08 ± 0.02 log(CS); $p = 0.001$) and the comparisons of the achromatic, M- and L-cone type with the S-cone type (achromatic 0.57 ± 0.02 log(CS) vs. M-cone 0.65 ± 0.02 log(CS) vs. L-cone 0.59 ± 0.02 log(CS); all $p < 0.0001$). Achromatic and chromatic cone types were equally influenced by diffusion, as no interaction was found between the factors.

3.2.3. Level of Diffusion

Slight differences were found in the results between the diffusion conditions. Averaging over all adaptation times, cone types, and spatial frequencies, the condition of 0.8 Bangerter foil showed reduced CS values (1.09 ± 0.06 log(CS)) compared to the 0.4 Bangerter foil condition (1.15 ± 0.06 log(CS)) and control condition (1.13 ± 0.06 log(CS)). Statistical analysis exhibited significant effect for the 0.8 Bangerter foil separately compared to the control CS (-0.04 ± 0.02 log(CS); $p = 0.05$) and 0.4 Bangerter foil CS (-0.06 ± 0.02 log(CS); $p = 0.0008$). However, no significant effect was found between control and 0.4 Bangerter foil condition (0.02 ± 0.02 log(CS); $p = 0.40$). The level of diffusion did not show significant interactions with spatial frequency, cone type, and adaptation time.

3.2.4. Contrast Adaptation

Differences in CS were found at the different measuring points, while the adaptation time significantly influenced CS ($p < 0.0001$). Here, post hoc testing showed effects between the single levels, see Figure 5. Significant outcomes were found between 0 and 90 min (0.12 ± 0.02 log(CS); $p < 0.0001$) of adaptation and between 30 and 90 min of adaptation (0.08 ± 0.02 log(CS); $p < 0.0001$), but not between 0 and 30 min (0.03 ± 0.02 log(CS); $p = 0.14$). However, CS was slightly reduced over the time (T_0 1.17 ± 0.06 log(CS), T_{30} 1.14 ± 0.06 log(CS) and T_{90} 1.06 ± 0.06 log(CS)). As no interactions were found between adaptation time and the other factors, no significant influence of Bangerter foil density or of the cone types were revealed.

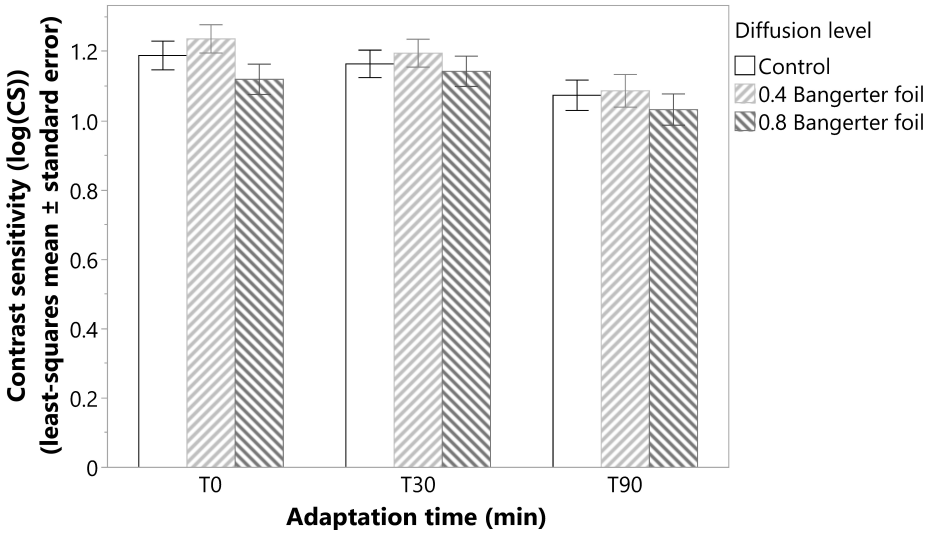

Figure 5. Least-squares mean ± standard error in log(CS) for the different diffusion levels over the adaptation time in min ($n = 19$ participants).

4. Discussion

The current study investigated the effect of different levels of peripheral contrast reduction in central achromatic and cone type specific CS to show if there is a retinal signal alteration or interaction from periphery to center. All influence factors (spatial frequency, cone type, diffusion level, and adaptation time) showed a significant effect on CS, without revealing relevant interactions. The following findings contributed to further understandings of processing and adaptation mechanisms.

The higher spatial frequency of 12 cpd produced lower CS compared to 3 cpd among all conditions compared to 3 cpd. This is already known from previous literature in context of the CS function, while there is an expected sensitivity peak at 2–5 cpd and sensitivities at smaller or greater frequencies than the peak frequency are lower [34]. Moreover, CS at 12 cpd exhibited higher deviations, which might be explained by the fact that contrast at higher spatial frequencies is harder to detect [33]. Furthermore, the results of this study showed lower sensitivities compared to the previous literature of Taylor et al. and Schilling et al. [18,33], although the participants wore their individual correction and an accommodation addition lens to reduce accommodation fluctuations. These discrepancies of previous and current CS results are due to different test procedures (e.g., two- or four-alternative forced-choice, 2IFC, method of adjustment) [33,35,36] and stimulus types (e.g., optotypes, sinusoidal pattern, silent substitution) [18,33,35,36]. Here, the four-alternative forced-choice Tuebingen CS Test figured as the basis for use in this study [33], as well as the stimulus types based on silent substitution. [18]

Differences in cone type CS were found in this study as well, which is in accordance with Taylor et al. [18]. In both studies, the S-cone type exhibited the lowest CS compared to the M-cone, L-cone, and achromatic conditions, which is explained by the filtering of short-wavelength light by crystalline lens and macular pigment [37], lacking in central fovea and lower distribution among the retina [38,39], as well as decreased spatial resolution compared to M- and L-cones [19]. Achromatic, M-, and L-cone type showed similar sensitivities since stimuli are detected by a highly sensitive pathway mechanism [18].

Furthermore, longitudinal chromatic aberration, a color signal, can shift the focal plane, which in turn can produce blur [12,18]. On the one hand, chromatic aberration is associated with adaptation phenomena [12], and on the other hand, contrast adaptation was found to be independent from longitudinal chromatic aberration [9]. Consequently, the chromatic effect was not controlled in the current study and thus could not be ruled out, although the stimulus time was limited to 153 ms. Another limitation is that cone types can be silenced at the level of phototransduction, but not on the output level [40]. Consequently, the silenced cones will still respond with a decreased signal, whereas the targeted cone type

recognizes a light intensity increase [40]. Furthermore, the standard luminosity function $v(\lambda)$ figured as the baseline for the described monitor calibration. This function was not individually obtained for each study participant. Consequently, this could lead to a slight imbalance among subjects in the brightness perception of the different test stimuli.

Surprisingly, the exposure to the 0.8 Bangerter foil condition revealed a higher impact in CS compared to the higher Bangerter foil of 0.4 density. The latter did not show any significant effect compared to the control condition. Consequently, the influence on visual performance depends on the level of the diffusion. Previous studies found similar results for different densities of Bangerter foils [12,41,42]. Especially, 0.4 and 0.8 Bangerter foil found to perform similarly [42]. Moreover, Bangerter foils demonstrated variations in quality, scattering characteristics, and impact in vision as the foils do not always comply with the manufacturer's specifications [41,42]. Therefore, the same Bangerter foil was used for all participants in this study. Furthermore, the Bangerter foils reduced visual acuity by always 0.1 logMAR steps (0.8 Bangerter foil) and 0.5 logMAR steps (0.4 Bangerter foil). Therefore, it did not create the same resulting visual acuities among participants, as this is dependent on the individual baseline acuity. To the authors best knowledge, the current approach is more meaningful, as it is also used in the myopia control spectacles [16,17].

So far, CS was only measured centrally after central adaptation [6,7,12,20–24] or peripherally after peripheral adaptation [6,7,22,25], but not its translation from the peripheral to the central retina. Regarding full-field imposed Bangerter foils, previous studies found an improvement of the visual performance after short-term adaptation to diffusion [12]. However, Villa-Carpes et al. did not find a lasting effect as the visual acuity was restored after removing the 0.6 Bangerter foils [12]. Teoh et al. found contrary results, as the visual acuity was reduced during exposure to Bangerter foils [23]. Investigations of spatial visual performance also found a reduction in CS in addition with diffusion [43]. Other studies focused on the effect on axial length, which is one important metric parameter in refractive development. Therefore, no beneficial changes of Bangerter foils were found in context of myopia treatment, consequently a reduction in axial length [23,24]. Moreover, in a primate study, it was found that Bangerter filter induced form deprivation myopia due to retinal image degradation [44]. According to a novel spectacle lens design including peripheral diffusion with a clear central zone, an early and non-peer-reviewed clinical study showed beneficial effects on refractive error reduction and reduced axial length progression [16,17]. Consequently, the results of the animal study [44] and the preliminary results of the human clinical study [16,17] are conflicting. The underlying technology of diffusion between the novel lens design and Bangerter foils probably differ from each other [45]. It is also worth mentioning that a clear central aperture smaller than the pupil size affects vision of the pupil periphery, as the pupil is a critical factor for adaptation processes [12,15,46]. Therefore, a clear central zone of 8.0 mm was chosen in this study to avoid crosstalk at the peripheral pupil area and no scattering can occur in this way. After all, previous findings are somehow contradictory and retinal mechanisms based on contrast reduction are still unclear, especially in the context of refractive development and its regulation. This study aimed to add information in adaptation procedures regarding peripheral contrast reduction. Additionally, comfort and compliance are maintained for the wearer due to a clear central aperture.

Contrast adaptation was not found neither for the 0.4 nor for the 0.8 Bangerter foil condition in the current study but a reduction in CS over the time. Main changes exhibited between 30 and 90 min of adaptation, while in the first 30 min no significant effect was found in CS. As mentioned above, Villa-Carpes et al. found an adaptation to 0.6 Bangerter foil after 40 min of adaption, except when exposed to full-field diffusion [12]. Nevertheless, contrast adaptation was found to be a signal for eye growth [44,47]. Long-term adaptation processes to retinal contrast reduction need to be investigated to evaluate lasting effects in refractive development. Furthermore, as peripheral contrast reduction imposed by 0.4 Bangerter foil affected central CS in this study, there might be a retinal translation from periphery to center—although contrast adaptation was associated with cortical processes,

so far [12,15,48]. Moreover, Maniglia et al. suggest cortical interactions between fovea and periphery [49], while contrast sensitivity can be modulated by effects of surround suppression [50], lateral masking [51], and other complex network interconnections [52]. This study, however, cannot distinguish, based on its psychophysical procedure, whether these findings underlie retinal and/or cortical interactions. Consequently, further studies are required to investigate optical, retinal, and neural adaptation mechanisms.

5. Conclusions

The study investigated central achromatic and chromatic CS for different peripheral contrast reduction levels with up to 90 min of adaptation time. Here, the lower diffusion levels affected central CS more than higher diffusion levels compared to the control condition. However, a reduction instead of increase in CS was found over time. These psychophysical findings figure as a basis for future research and clinical purposes to fully understand retinal and cortical adaptation mechanisms behind the potential myopia control strategy using peripheral contrast reduction.

Supplementary Materials: The following supplementary material is available online at https://gin.g-node.org/antonia.neumann/photonics-1601950.git, Table S1: Akaike information criterion (AIC) comparison of linear mixed model analysis. Within the model analysis, contrast sensitivity (CS) figured as numeric dependent variable, with participants (subjects, $n = 19$) as random effect and four within-subject factors: Refractive group (Group; non-myopes with a refractive spherical equivalent >-0.5 D and myopes with a refractive spherical equivalent ≤ -0.5 D), stimuli type (ST; Achromatic, S-, M- and L-cone), spatial frequency (SF; 3 cpd and 12 cpd), diffusion level (D; control/without diffusion, 0.4 and 0.8 Bangerter foil each with a clear aperture of 8.0 mm) and adaptation time (Time; T0 – 0 min, T30 – 30 min and T90 – 90 min).

Author Contributions: Conceptualization, A.N., A.L., N.N., K.B. and S.W.; methodology, A.N., A.L. and K.B.; software, A.N., P.E. and Y.S.; validation, A.N.; formal analysis, A.N. and K.B.; investigation, A.N.; resources, S.W.; data curation, A.N.; writing—original draft preparation, A.N.; writing—review and editing, A.N., A.L., N.N., Y.S., P.E., K.B. and S.W.; visualization, A.N. and K.B.; supervision, A.L., K.B. and S.W.; project administration, S.W.; funding acquisition, S.W. All authors have read and agreed to the published version of the manuscript.

Funding: Funding was received from Eberhard Karls University Tübingen (ZUK 63) as part of the German Excellence initiative from the Federal Ministry of Education and Research (BMBF). Further funding was received from Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of University of Tübingen. The funders did not have any additional role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Institutional Review Board Statement: This prospective study was carried out at the Institute for Ophthalmic Research at the University of Tübingen. The study protocol followed the Declaration of Helsinki and data protection regulations. Approval was obtained by the ethics committee of the Faculty of Medicine of the University of Tübingen.

Informed Consent Statement: Written informed consent was obtained from all participants after the content and possible consequences of the study had been explained.

Data Availability Statement: Data available on request.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CS	Contrast sensitivity
L-cones	Long-wavelength light sensitive cones
M-cones	Middle-wavelength light sensitive cones
S-cones	Short-wavelength light sensitive cones

References

1. Wolffsohn, J.S.; Flitcroft, D.I.; Gifford, K.L.; Jong, M.; Jones, L.; Klaver, C.C.; Logan, N.S.; Naidoo, K.; Resnikoff, S.; Sankaridurg, P.; et al. IMI–myopia control reports overview and introduction. *Investig. Ophthalmol. Vis. Sci.* **2019**, *60*, M1–M19. [CrossRef] [PubMed]
2. Morgan, I.G.; French, A.N.; Ashby, R.S.; Guo, X.; Ding, X.; He, M.; Rose, K.A. The epidemics of myopia: Aetiology and prevention. *Prog. Retin. Eye Res.* **2018**, *62*, 134–149. [CrossRef] [PubMed]
3. Jonas, J.B.; Ang, M.; Cho, P.; Guggenheim, J.A.; He, M.G.; Jong, M.; Logan, N.S.; Liu, M.; Morgan, I.; Ohno-Matsui, K.; et al. IMI prevention of myopia and its progression. *Investig. Ophthalmol. Vis. Sci.* **2021**, *62*, 6. [CrossRef] [PubMed]
4. Jong, M.; Jonas, J.B.; Wolffsohn, J.S.; Berntsen, D.A.; Cho, P.; Clarkson-Townsend, D.; Flitcroft, D.I.; Gifford, K.L.; Haarman, A.E.; Pardue, M.T.; et al. IMI 2021 yearly digest. *Investig. Ophthalmol. Vis. Sci.* **2021**, *62*, 7. [CrossRef]
5. Kerber, K.L.; Thorn, F.; Bex, P.J.; Vera-Diaz, F.A. Peripheral contrast sensitivity and attention in myopia. *Vis. Res.* **2016**, *125*, 49–54. [CrossRef]
6. Gao, Y.; Webster, M.A.; Jiang, F. Dynamics of contrast adaptation in central and peripheral vision. *J. Vis.* **2019**, *19*, 23. [CrossRef]
7. Greenlee, M.W.; Georgeson, M.A.; Magnussen, S.; Harris, J.P. The time course of adaptation to spatial contrast. *Vis. Res.* **1991**, *31*, 223–236. [CrossRef]
8. Heinrich, T.S.; Bach, M. Contrast adaptation in retinal and cortical evoked potentials: No adaptation to low spatial frequencies. *Vis. Neurosci.* **2002**, *19*, 645. [CrossRef]
9. Kraft, C.; Leube, A.; Ohlendorf, A.; Wahl, S. Contrast adaptation appears independent of the longitudinal chromatic aberration of the human eye. *JOSA A* **2019**, *36*, B77–B84. [CrossRef]
10. McGonigle, C.; van der Linde, I.; Pardhan, S.; Engel, S.A.; Mallen, E.A.; Allen, P.M. Myopes experience greater contrast adaptation during reading. *Vis. Res.* **2016**, *121*, 1–9. [CrossRef]
11. Ohlendorf, A.; Schaeffel, F. Contrast adaptation induced by defocus—A possible error signal for emmetropization? *Vis. Res.* **2009**, *49*, 249–256. [CrossRef] [PubMed]
12. Villa-Carpes, J.A.; Bueno, J.M.; Fernández, E.J. Visual Adaptation to Scattering in Myopes. *Photonics* **2021**, *8*, 274. [CrossRef]
13. Aleman, A.C.; Wang, M.; Schaeffel, F. Reading and myopia: Contrast polarity matters. *Sci. Rep.* **2018**, *8*, 10840. [CrossRef] [PubMed]
14. Collins, M.J.; Buehren, T.; Iskander, D.R. Retinal image quality, reading and myopia. *Vis. Res.* **2006**, *46*, 196–215. [CrossRef]
15. George, S.; Rosenfield, M. Blur adaptation and myopia. *Optom. Vis. Sci.* **2004**, *81*, 543–547. [CrossRef]
16. SightGlass Vision, Inc. Control of Myopia Using Novel Spectacle Lens Designs (CYPRESS), 2018–2022. Available online: https://clinicaltrials.gov/ct2/show/NCT03623074 ClinicalTrials.gov (accessed on 2 July 2020).
17. Rappon, J.; Neitz, J.; Neitz, M. Novel DOT Lenses from SightGlass Vision Show Great Promise to Fight Myopia. 2020. Available online: https://reviewofmm.com/novel-dot-lenses-from-sightglass-vision-show-great-promise-to-fight-myopia/ (accessed on 2 July 2020).
18. Taylor, C.P.; Shepard, T.G.; Rucker, F.J.; Eskew, R.T. Sensitivity to S-cone stimuli and the development of myopia. *Investig. Ophthalmol. Vis. Sci.* **2018**, *59*, 4622–4630. [CrossRef]
19. Williams, D.; Sekiguchi, N.; Brainard, D. Color, contrast sensitivity, and the cone mosaic. *Proc. Natl. Acad. Sci. USA* **1993**, *90*, 9770–9777. [CrossRef]
20. Blakemore, C.; Campbell, F.W. Adaptation to spatial stimuli. *J. Physiol.* **1969**, *200*, 11P–13P.
21. Foley, J.M.; Boynton, G.M. Forward pattern masking and adaptation: Effects of duration, interstimulus interval, contrast, and spatial and temporal frequency. *Vis. Res.* **1993**, *33*, 959–980. [CrossRef]
22. Williams, D.; Wilson, H.; Cowan, J. Localized effects of spatial-frequency adaptation. *JOSA* **1982**, *72*, 878–887. [CrossRef]
23. Teoh, S.C.; Collins, M.J.; Read, S.A. The short-term effect of diffuse and defocus blur on axial length and vision. *Investig. Ophthalmol. Vis. Sci.* **2020**, *61*, 2698.
24. Teoh, S.C.; Collins, M.J.; Read, S.A.; Pieterse, E. Axial length change with short-term exposure to visual stimuli with a limited range of spatial frequencies. *Investig. Ophthalmol. Vis. Sci.* **2021**, *62*, 1340.
25. Sharpe, C.; Tolhurst, D. Orientation and spatial frequency channels in peripheral vision. *Vis. Res.* **1973**, *13*, 2103–2112. [CrossRef]
26. Seidemann, A.; Schaeffel, F. An evaluation of the lag of accommodation using photorefraction. *Vis. Res.* **2003**, *43*, 419–430. [CrossRef]
27. Brainard, D.H. The psychophysics toolbox. *Spat. Vis.* **1997**, *10*, 433–436. [CrossRef] [PubMed]
28. Kleiner, M.; Brainard, D.; Pelli, D. What's new in Psychtoolbox-3? *Perception* **2007**, *36*, 1–16.
29. Shen, Y.; Dai, W.; Richards, V.M. A MATLAB toolbox for the efficient estimation of the psychometric function using the updated maximum-likelihood adaptive procedure. *Behav. Res. Methods* **2015**, *47*, 13–26. [CrossRef]
30. Estévez, O.; Spekreijse, H. The "silent substitution" method in visual research. *Vis. Res.* **1982**, *22*, 681–691. [CrossRef]
31. Stockman, A.; Sharpe, L.T.; Fach, C. The spectral sensitivity of the human short-wavelength sensitive cones derived from thresholds and color matches. *Vis. Res.* **1999**, *39*, 2901–2927. [CrossRef]
32. Stockman, A.; Sharpe, L.T. The spectral sensitivities of the middle-and long-wavelength-sensitive cones derived from measurements in observers of known genotype. *Vis. Res.* **2000**, *40*, 1711–1737. [CrossRef]
33. Schilling, T.; Ohlendorf, A.; Leube, A.; Wahl, S. TuebingenCSTest—A useful method to assess the contrast sensitivity function. *Biomed. Opt. Express* **2017**, *8*, 1477–1487. [CrossRef]

34. Kelly, D. Visual contrast sensitivity. *Opt. Acta Int. J. Opt.* **1977**, *24*, 107–129. [CrossRef]
35. Pelli, D.G.; Bex, P. Measuring contrast sensitivity. *Vis. Res.* **2013**, *90*, 10–14. [CrossRef] [PubMed]
36. Owsley, C. Contrast sensitivity. *Ophthalmol. Clin. N. Am.* **2003**, *16*, 171–177. [CrossRef]
37. Stockman, A.; MacLeod, D.I.; Johnson, N.E. Spectral sensitivities of the human cones. *JOSA A* **1993**, *10*, 2491–2521. [CrossRef] [PubMed]
38. Williams, D.R.; MacLeod, D.I.; Hayhoe, M.M. Foveal tritanopia. *Vis. Res.* **1981**, *21*, 1341–1356. [CrossRef]
39. Williams, D.R.; MacLeod, D.I.; Hayhoe, M.M. Punctate sensitivity of the blue-sensitive mechanism. *Vis. Res.* **1981**, *21*, 1357–1375. [CrossRef]
40. Kamar, S.; Howlett, M.H.; Kamermans, M. Silent-substitution stimuli silence the light responses of cones but not their output. *J. Vis.* **2019**, *19*, 14. [CrossRef]
41. Pérez, G.M.; Archer, S.M.; Artal, P. Optical characterization of Bangerter foils. *Investig. Ophthalmol. Vis. Sci.* **2010**, *51*, 609–613. [CrossRef]
42. Van Den Berg, T.J. Analysis of intraocular straylight, especially in relation to age. *Optom. Vis. Sci. Off. Publ. Am. Acad. Optom.* **1995**, *72*, 52–59. [CrossRef]
43. Perez, G.M.; Manzanera, S.; Artal, P. Impact of scattering and spherical aberration in contrast sensitivity. *J. Vis.* **2009**, *9*, 19.1–19.10. [CrossRef] [PubMed]
44. Smith III, E.L.; Hung, L.F. Form-deprivation myopia in monkeys is a graded phenomenon. *Vis. Res.* **2000**, *40*, 371–381. [CrossRef]
45. Neitz, J.; Kuchenbecker, J.; Neitz, M. Ophthalmic Lenses for Treating Myopia. U.S. Patent 10571717, 25 February 2020.
46. Diez, P.S.; Schaeffel, F.; Wahl, S.; Ohlendorf, A. Accommodation responses following contrast adaptation. *Vis. Res.* **2020**, *170*, 12–17. [CrossRef] [PubMed]
47. Diether, S.; Gekeler, F.; Schaeffel, F. Changes in contrast sensitivity induced by defocus and their possible relations to emmetropization in the chicken. *Investig. Ophthalmol. Vis. Sci.* **2001**, *42*, 3072–3079.
48. Demb, J.B. Functional circuitry of visual adaptation in the retina. *J. Physiol.* **2008**, *586*, 4377–4384. [CrossRef]
49. Maniglia, M.; Contemori, G.; Marini, E.; Battaglini, L. Contrast adaptation of flankers reduces collinear facilitation and inhibition. *Vis. Res.* **2022**, *193*, 107979. [CrossRef]
50. Xing, J.; Heeger, D.J. Center-surround interactions in foveal and peripheral vision. *Vis. Res.* **2000**, *40*, 3065–3072. [CrossRef]
51. Polat, U.; Sagi, D. Lateral interactions between spatial channels: Suppression and facilitation revealed by lateral masking experiments. *Vis. Res.* **1993**, *33*, 993–999. [CrossRef]
52. Cannon, M.W.; Fullenkamp, S.C. Spatial interactions in apparent contrast: Inhibitory effects among grating patterns of different spatial frequencies, spatial positions and orientations. *Vis. Res.* **1991**, *31*, 1985–1998. [CrossRef]